ENHANCING INJURY PROTECTION CAPABILITIES OF ARMY COMBAT HELMETS

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ABSTRACT

Traditionally, combat helmet design has focused on improving ballistic protection, but there has been recent interest in providing better protection from blunt impacts as well. In the military environment, many factors can produce blunt force head injury, including ground vehicle or aircraft mishaps, falls, etc. This paper outlines recent accomplishments of the combat helmet program at the U.S. Army Aeromedical Research Laboratory (USAARL) that have contributed measurably to enhanced Soldier survival in current combat operations.

1. INTRODUCTION

Protecting the Soldier's head from injury is critically important to individual survivability and mission success. In peacetime, most head injury in the military results from accidental exposure to blunt force and is non-penetrating (i.e., closed head trauma). In wartime, there is the additional hazard of penetrating head trauma resulting from high speed projectiles (e.g,, shrapnel, bullets). In the past, helmets designed for use in combat have focused on protecting the wearer from penetrating head trauma, with little attention paid to insulating the head and brain from blunt force trauma. Conversely, military helmets designed for occupations at high risk for closed head injury, such as helicopter crewmembers, provide little penetration protection. The ideal combat helmet would provide protection from both penetrating and blunt forces.

Recent developments in materials science, combined with accumulating experience from current combat operations, have driven a program at the U.S. Army Aeromedical Research Laboratory (USAARL) to improve the overall performance of Army helmet systems. This paper provides highlights of our research supporting recent improvements in blunt injury protection to the Army's ballistic protective helmet (Brozoski and McEntire, 2003; Trumble, McEntire, and Crowley, 2005a, 2005b; McEntire and Whitley, 2005; Brozoski, Lang, and Crowley, 2006; McEntire, et al., 2006).

2. MATERIALS RESEARCH

Protection from blunt force depends largely on the dissipation of energy by the helmet, rather than by the wearer's head and brain. Soldier protection must keep pace with improvements in material development. In one recent evaluation at USAARL, a variety of energy-absorbing materials were evaluated for performance and suitability as supplemental liners for existing ballistic protective helmets or for future aircrew helmet improvements. For nearly 45 years, Army rotary-wing aircrew helmets have incorporated polystyrene liners – of varying densities and thickness – as the primary means of attenuating impact energy. In addition to these materials, aluminum foams, a semi-rigid, closed-cell polypropylene foam, and an open-cell polyurethane-based foam were assessed. For ease of identification, a reference symbol was assigned to each material (Table 1).

Table 1. Energy attenuating materials evaluated.

Material type	Symbol	Density (pcf)
EPS	EPS-1.6	1.6
	EPS-3.7	3.7
	EPS-5.7	5.7
Aluminum foam	AL-5-10.1	10.1
	AL-10-5.0	5.0
	AL-10-10.1	10.1
Polypropylene	PP-5.5	5.5
Polyurethane	PU-6.1	6.1

Note: Aluminum foams were manufactured from alloy 6101. Symbols were assigned based on material type, mass density, and, for aluminum foams, the foam's cell density [the number of pores per inch (ppi) of material]. The aluminum foams tested had cell densities of 5 and 10 ppi.

2.1 Experimental procedure

Material test specimens were subjected to quasi-static compression testing. Specimens were loaded at 5 inches per second through 80 percent of their original gage length. Compressive force was recorded as a function of compressive displacement for each specimen.

To determine the effect of loading rate on each material's energy attenuation characteristics, dynamic compression tests were conducted using a monorail drop tower conforming to ANSI Z90.1-1992 (ANSI, 1992); an 11.0-pound (lb) flat impactor (Figure 1) was fitted to the tower and dropped onto material samples at 7.07 feet per second (fps), 10.0 fps, and 14.14 fps. For each test, the impact acceleration and transmitted force were recorded.

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The acceleration data were subsequently double integrated to determine impactor displacement.

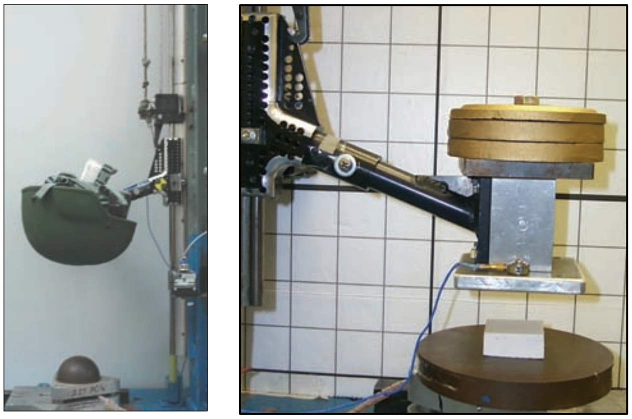

Figure 1. Dynamic impact test equipment. An Army combat helmet is fitted to the monorail drop tower (left). The variable weight, flat impactor (right) is fitted to the monorail drop tower during dynamic material testing.

2.2 Data analysis

Static and dynamic compressive stress-strain curves were generated for each test specimen. The energy-absorbing materials were evaluated based on information derived from their respective stress-strain curves. First, the loading portion of each material's quasi-static stress-strain curve was compared to recommended stress-strain properties for energy-absorbing materials used to cushion the head during impact (Figure 2). The area, or "corridor," bounded by the two curves represents the recommended range of stress-strain properties intended to limit peak head acceleration values to 160 G for material thicknesses of one inch or less (USAAVSCOM, 1989). The material exhibiting the best agreement with the recommended properties received the highest rank of 1.

Materials were also evaluated with respect to three additional metrics. The first of these was EA ratio, which represents the amount of specific energy dissipated by a material during compression. The materials were ranked based on the magnitude of their EA ratio; the material having the greatest EA ratio was assigned the highest rank of 1. Materials were also evaluated based on the thickness and mass of material theoretically necessary to limit peak headform acceleration to 175 G assuming a headform mass of 11.0 lbs, an impact velocity of 14.14 fps, and a contact area between the headform and material of 25 square inches (in^2). The material requiring the least thickness received the highest ranking of 1. Likewise, the lightest weight material was given the highest rank of 1.

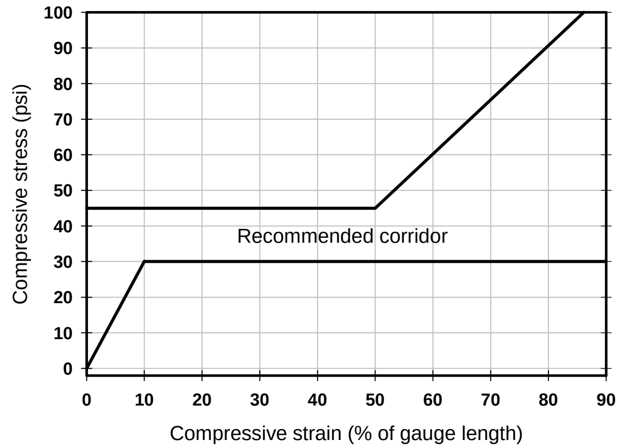

Figure 2. Recommended stress-strain properties for head impact energy attenuation materials (USAAVSCOM, 1989).

2.3 Material performance

The loading portion of each material's quasi-static stress strain curves is presented in Figure 3. Also presented is the "corridor" defined by the recommended stress-strain properties for energy absorbing materials used to cushion head impacts (USAAVSCOM, 1989) (originally presented in Figure 2).

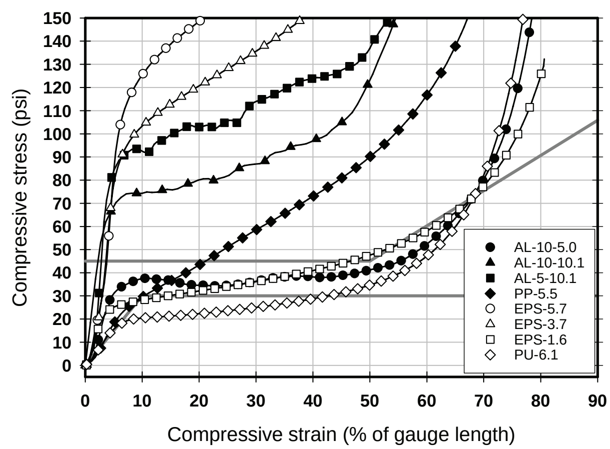

Figure 3. Quasi-static loading curves. To better illustrate the relationship between the material stress-strain curves and recommended stress-strain corridor (heavy gray lines), the vertical scale has been limited to 150 psi.

Of the eight materials, the loading curves of AL-10-5.0, EPS-1.6, and PU-6.1 fit best within the stress-strain corridor (Table 2). AL-10-5.0 was ranked highest, as its loading curve remained entirely within the corridor until nearly 67 percent compressive strain (Figure 3). Yield point stresses for EPS-3.7, EPS-5.7, AL-5-10.1, and AL-10-10.1 were well above the upper boundary of the stress-strain corridor (Figure 3). As such, these four materials were ranked lowest among the eight in this portion of the overall assessment (Table 2).

Table 2. Material rankings based on agreement with stress strain corridor.

Symbol	Rank
EPS-1.6	2
EPS-3.7	7
EPS-5.7	8
AL-5-10.1	6
AL-10-5.0	1
AL-10-10.1	5
PP-5.5	4
PU-6.1	3

Each material's EA ratio and corresponding rank are presented in Table 3. The theoretical thickness and mass of material needed to limit the peak acceleration of an 11.0-lb headform to 175 Gs assuming an impact velocity of 14.14 fps and contact area of 25.0 in^2 are presented in Table 4.

Table 3. Energy absorption ratio and corresponding material rankings.

Symbol	EA ratio	Rank
EPS-1.6	0.775	7
EPS-3.7	0.932	5
EPS-5.7	0.942	4
AL-5-10.1	0.946	3
AL-10-5.0	0.962	2
AL-10-10.1	0.970	1
PP-5.5	0.766	8
PU-6.1	0.838	6

Table 4. Ranking based material thickness and mass.

Symbol	Thickness (in)	Rank	Mass (lbs)	Rank
EPS-1.6	0.92	2	0.021	1
EPS-3.7	112.10	7	6.001	6
EPS-5.7	106.50	6	8.783	7
AL-5-10.1	146.18	8	21.360	8
AL-10-5.0	0.86	1	0.062	2
AL-10-10.1	8.92	5	1.303	5
PP-5.5	2.10	4	0.167	4

Each material's total score is presented in Table 5. It should be noted that AL-5-10.1, EPS-3.7, and EPS-5.7 all received a score of 25. In this analysis, each metric is considered equally. Therefore, these three materials tied for the overall rank of 6 (out of 8).

Table 5. Overall material scores.

Symbol	Rank from individual metrics				Total
	Corridor	EA ratio	Thick-ness	Mass	
EPS-1.6	2	7	2	1	12
EPS-3.7	7	5	7	6	25
EPS-5.7	8	4	6	7	25
AL-5-10.1	6	3	8	8	25
AL-10-5.0	1	2	1	2	6
AL-10-10.1	5	1	5	5	16
PP-5.5	4	8	4	4	20
PU-6.1	3	6	3	3	15

2.4 Discussion

Several parameters must be considered when designing protective headgear. Among these are the impact protection, acoustic protection, and dynamic stability and retention provided by the helmet, as well as overall helmet size and mass. A helmet's energy-absorbing liner directly influences three of the parameters. Most importantly, the energy-absorbing liner influences the helmet's impact protection. Also, the energy-absorbing liner must be thick enough to provide the necessary level of impact protection, but also fit within the confines of the helmet shell. Thick energy-absorbing liners require larger helmet shells, increasing the helmet's weight and size. Finally, the mass of the energy-absorbing liner contributes to the overall mass of the helmet. Minimizing its mass and size reduces the overall helmet system mass and size.

2.5 Conclusions

Of the eight materials evaluated, AL-10-5.0 was found to be the most suitable for use as a helmet energy-absorbing material in helmets where repeated impacts to the same site are not a requirement. While not ranked first in all metrics, AL-10-5.0 appears to offer the best compromise between protection, space, and weight.

AL-5-10.1, EPS-3.7, and EPS-5.7 tied with the highest total, and should therefore be considered the least suitable of the eight materials evaluated for use in energy-absorbing liners. Due to their high yield stresses, use of these materials would likely result in head accelerations in excess of 175 G – currently recommended by USAARL as the acceleration threshold for impacts to the headband region of a helmet.

3. NEW MATERIALS FOR PARATROPER BLUNT IMPACT PROTECTION

One important population at risk for blunt head injury in the military is paratroopers. Even mild head injury, or concussion, on the drop zone can adversely affect mission effectiveness. There may also be a cumulative traumatic brain injury (TBI) effect from repetitive head impacts compounding the sequelae. There is an obvious need to protect the Soldier in these environments and minimize the head injury rate.

3.1 Objectives

The purpose of this research project was to determine whether recent advances in energy-attenuating materials could improve blunt injury protection for Army paratroopers, while not reducing protection against penetrating ballistic trauma

3.2 Material selection

The USAARL placed a Commerce Business Daily (CBD) announcement for industry to submit proposed helmet retention and impact protection systems. Initially, two companies submitted a total of six different candidate protective systems (Table 6, Systems C through H). The airborne-configured PASGT helmet served as the control (Table 6, System A); a modified airborne PASGT helmet equipped with the Parachutist Impact Liner (PIL) was included as System B. The PIL is available in the Army inventory and consists of three-pieces of ¼ inch thick polyolefin foam sheet installed inside the PASGT shell. Previous testing of the airborne-configured PASGT helmet equipped with the PIL showed a 20 percent reduction in transmitted acceleration versus the standard airborne PASGT helmet configuration (McEntire, Mason, Austinhirst, 1996).

Table 6. Protective systems tested.

System	Description
A	Current airborne PASGT
B	Current airborne PASGT with the PIL
C	Company A – Improved PASGT Inner Helmet Suspension and Retention System
D	Company A – Ballistic Protective Law Enforcement Helmet (BPLEH)
E	Company A – Lightweight Helmet Marine (LWH)
F	Company A – Tactical Ballistic Helmet (TBH)
G	Company B – Ballistic Liner Suspension System (BLSS)
H	Company B – Kevlar® Liner Upgrade (KLU)

3.3 Experimental procedures

Blunt impact and dynamic retention performance of the current issue airborne PASGT helmet configuration was evaluated against the performance of the candidate systems. By using the current system as a baseline, the testing would determine if a candidate system was better than the currently fielded system.

3.3.1 Impact attenuation

All impact tests were conducted using the USAARL vertical monorail drop tower (Figure 1, left). Impact sites along with headform orientation are designated in Table 7.

Table 7. Headform orientation by impact site.

Impact site	Head pitch angle (deg)	Head roll angle (deg)
Front	25	0
Crown	10	0
Left Side	0	25
Right Side	0	25
Left Ear	0	3
Right Ear	0	3
Rear	25	0
Nape	90	0

Test helmets were fitted to the headform and then released from appropriate drop heights to achieve target impact velocities of 10.0, 14.14, and 17.32 fps. These velocities are close to the reported decent velocities of paratroopers (19.0 -23.0 fps) (DOD, 1996). Testing combat helmets at impact velocities greater than 17.32 fps, i.e., at 19.0 fps, would have resulted in physical damage to the test equipment.

Headform impact acceleration was measured by a single-axis accelerometer mounted at the center of mass of the test headform. The accelerometer data were filtered in accordance with Society of Automotive Engineers (SAE) Recommended Practice J211, Part 1 (1995).

3.3.2 Dynamic stability

Helmet dynamic stability tests were conducted using the USAARL mini-sled (Figure 4). In these tests, helmets were fitted snugly to the Hybrid II headform. The headform and helmets were fitted with reflective markers to facilitate optical tracking. The 100-pendulum was raised to a drop height sufficient to produce mini-sled acceleration of 33-G with a velocity change of approximately 17 fps. The carriage was propelled rearward by the impacting pendulum forcing the head and neck into flexion, resulting in helmet rotation relative to the head. This motion was recorded using high-speed digital video cameras recording at 1000 frames per second.

The high-speed video images were digitized and analyzed. The helmet and head targets were tracked using motion analysis software to obtain the angular displacement of the helmet relative to the Hybrid II headform.

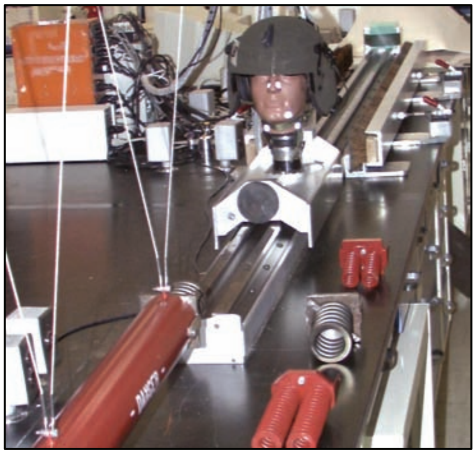

Figure 4. Mini sled test apparatus. Shown in the foreground is the 100-pound pendulum. The white dots on the headform's nose, chin, and neck are reflective targets used for optically tracking head and helmet motion.

3.4 Results

Of the systems tested (Table 6), System A (the currently issued airborne PASGT helmet) provided the best impact protection. No candidate helmets (B – H) offered consistently better impact protection (i.e., lower transmitted headform accelerations) than System A at the three target impact velocities.

System A provided the best dynamic retention. Systems B – H exhibited more helmet rotation relative to the test headform than did System A. Large amounts of helmet rotation relative to the head are indicative of poor dynamic retention.

3.5 Follow-on investigation

Initial testing revealed that no candidate system provided better blunt impact protection than the current airborne-configured PASGT helmet. Therefore, two additional hybrid systems were identified and tested. One of the hybrid systems included the standard PASGT shell and sling suspension system with a nape pad constructed from a novel material with an improved three-point retention system with integrated chin and nape straps. The other hybrid helmet replaced the PASGT sling suspension system with energy-absorbing foam pads, also with the same three-point retention system (Table 8).

As in the previous test series, Systems 1 – 3 were subjected to impact attenuation and dynamic retention evaluations.

Table 8. Systems tested during follow-on investigation.

System	Description
1	Current airborne PASGT
2	Airborne PASGT with novel nape pad, PIL and candidate three-point retention harness
3	Airborne PASGT with Company B pads and candidate three-point retention harness

3.6 Conclusions

Both hybrid candidate systems provided improved overall performance in impact attenuation and dynamic stability compared to the current U.S. Army airborne helmet configuration. Overall, the configuration of the two helmet systems improved impact performance by approximately 25 percent.

This effort to improve blunt impact performance of the PASGT helmet was successful, and the key energy-absorbing materials validated in this program are now featured in the Army's new Advanced Combat Helmet (ACH).

4. ARMY COMBAT HELMET ANALYSIS

In 2004-5, the Vice Chief of Staff of the Army (VCSA) convened a task force to determine the best overall head protective system for Army Soldiers. The USAARL helmet biomechanics team contributed significantly to this multidisciplinary analysis effort, performing several studies that proved to be most useful to the Army Infantry Center and the VCSA. First, the USAARL provided detailed test data describing blunt impact performance of the ACH compared to the PASGT helmet. Second, USAARL engineers and flight surgeons conducted an assessment of fit and wear patterns. Third, an assessment of relative helmet coverage was conducted using a novel computer-mapping process.

4.1 ACH & PASGT helmet blunt impact performance

A major series of blunt impact assessments were performed on the PASGT, airborne PASGT with the PIL, and the ACH helmets (McEntire and Whitley, 2005). The intent of this study was to collect data for use in establishing the ACH blunt impact performance requirement.

The mean results indicated the ACH to have greater blunt impact protection than the two PASGT configurations at both impact velocity conditions. At both impact velocity test conditions, the differences were statistically significant between the ACH and standard PASGT, but not between the ACH and airborne PASGT with the PIL.

4.2 Combat helmet wear patterns

4.2.1 Study methods

Digital photographic images of U.S. Army Soldiers were collected from the Defense Visual Information (DVI) website. Images were selected for further study based on the ability to visualize the antero-lateral or lateral aspect of the Soldier's head and helmet, and the realism of the photo: photographs that appeared staged or posed were excluded. For the ACH, a total of 236 images were selected for evaluation. Similarly, a total of 231 images of the PASGT helmet were selected for review.

The final set of study photos were distributed to six subject matter experts (SMEs) for independent review. Four completed data sets were returned in time to be included in this analysis, resulting in an expert panel consisting of one flight surgeon, two infantry Sergeants Major (one active duty and one recently retired), and one helmet engineer.

Reviewers received instructions to assess helmet wear using their expert judgment as well as employing official U.S. Army fitting guidance for the ACH (DA, 2004a, 2004b, and 2004c) and the PASGT helmet (Natick Pamphlet 70-2, 2000). Judging criteria were standardized across the reviewers through the use of software that displayed an image selected at random and gave the reviewer a set of choices from which to select. Helmet wear was judged as "correct" or "incorrect." Incorrect wear patterns were further characterized with respect to pitch, roll, twist, and elevation on the head. Narrative comments regarding additional observations were collected.

4.2.2 Findings

Patterns of correct and incorrect wear of the PASGT and ACH helmets were identified. Training appeared to have a beneficial effect on helmet wear patterns

4.3 Head coverage

In response to the VCSA request, this USAARL study was designed to assess head coverage provided by various Army helmets..

4.3.1 Assessment methodology

The projected head coverage area provided by four combat helmets was evaluated. The helmets were the PASGT, ACH, Combat Vehicle Crewman's helmet (CVC), and Hybrid (a PASGT shell and ACH fitting pads) (Figure 5).

Appropriately-sized helmets were fitted to a medium size USAARL headform (USAARL, 1988). Helmet size was determined by the anthropometric measurements of the test headform and the published sizing criteria for each helmet type (DA, 2004a and 2004b; U.S. Army Natick Laboratories, 1978; Natick Pamphlet 70-2, 2000).

PASGT helmet ACH CVC

Figure 5. U.S. Army combat helmets.

Digital photographs of the bare and helmeted headform were taken from different perspective angles .After the digital images were collected and archived, all were analyzed using custom-designed software.

4.3.2 Findings

There is little difference in projected coverage area provided by a properly worn ACH and a properly worn PASGT helmet.

4.4 Conclusions

These studies were crucial in identifying key factors potentially contributing to helmet success. Authorized agencies may request additional details from frederick.brozoski@se.amedd.army.mil. The USAARL team was recognized for its contributions with the 2005 Wilber Payne Memorial Award for Excellence in Analysis (Large Group Category). The USAARL also recently completed a series of analyses for the VCSA's 2006 study to determine the feasibility of replacing the Combat Vehicle Crewman helmet with the ACH.

The USAARL biomechanics team has conducted innovative and award-winning engineering analyses of helmet performance that have measurably improved combat effectiveness and Soldier survivability.

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